

OPTICAL SPECTROSCOPY OF THE LARGE KUIPER BELT OBJECTS 136472 (2005 FY9) AND 136108 (2003 EL61)

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ABSTRACT

We present high signal precision optical reflectance spectra of the large Kuiper Belt objects 2005 FY9 and 2003 EL61. The spectrum of 2005 FY9 exhibits strong CH₄ ice bands. A comparison between the spectrum and a Hapke model indicates that the CH₄ bands are shifted 3.25 ± 2.25 Å relative to pure CH₄ ice, suggesting the presence of another ice component on the surface of 2005 FY9, possibly N₂ ice, CO ice, or Ar. The spectrum of 2003 EL61 is remarkably featureless. There is a hint of an O₂ ice band at 5773 Å; however, this feature needs to be confirmed by future spectroscopic observations of 2003 EL61 with a higher continuum signal precision sufficient to detect a second, weaker O₂ ice band at 6275 Å.

Key words: Kuiper Belt — techniques: spectroscopic

1. INTRODUCTION

Measuring the surface composition of Kuiper Belt objects (KBOs) may provide clues about the composition and environment of the primordial solar nebula, as well as the important evolutionary processes occurring in the outer solar system over the last 4.5 Gyr. Unfortunately, there are only a handful of KBOs known to exhibit ice absorption bands in their spectra. H₂O ice bands are seen in spectra of 1996 TO66 (Brown et al. 1999), Varuna (Licandro et al. 2001), Quaoar (Jewitt & Luu 2004), and Orcus (Fornasier et al. 2004a). CH₄ ice bands are seen in spectra of Pluto (Cruikshank et al. 1976; Fink et al. 1980; Grundy & Fink 1996); Neptune’s satellite Triton, which may be a captured KBO (Cruikshank et al. 1993); Eris (Brown et al. 2005); and 2005 FY9 (Licandro et al. 2006). There are perhaps a dozen objects that exhibit spectra with no ice absorption bands (Doressoundiram et al. 2003; Fornasier et al. 2004b).

The recent discovery of extraordinarily bright and large KBOs opens up a new opportunity for the physical and chemical studies of KBO surfaces with high signal precision optical reflectance spectroscopy. Bright objects make it possible to either carry out in-depth physical modeling of ice and mineralogical absorption bands or set stringent upper limits on the presence of such bands.

Here we present high signal precision optical reflectance spectra of KBOs 2005 FY9 and 2003 EL61. Both objects are candidates for membership in the newly defined class “dwarf planet.” The diameter of 2005 FY9 is estimated at 1600 km (Brown et al. 2007), while 2003 EL61 appears to be a highly elongated ellipsoid with axes of 1950×2500 km (Rabinowitz et al. 2006). For comparison, Pluto has a diameter of 2350 km. The KBOs 2005 FY9 and 2003 EL61 are among “scattered-near” objects (i.e., nonresonant, non-planet-crossing objects with Tisserand parameters less than 3, relative to Neptune) in the Deep Ecliptic Survey classification system (Elliot et al. 2005). The KBO 2005 FY9 has a perihelion distance q of 38.6 AU, an aphelion distance Q of 52 AU, a semimajor axis a of 45.3 AU, an inclination angle to the ecliptic i of 29° , and an eccentricity of 0.15. The KBO 2003 EL61 has $q = 35.1$ AU, $Q = 51$ AU, $a = 43.1$ AU, $i = 28^\circ$, and $e = 0.18$. For comparison, Pluto has $q = 29.7$ AU, $Q = 49$ AU, $a = 39.5$ AU, $i = 17^\circ$, and $e = 0.25$. At the time of observation, 2005 FY9 and 2003 EL61 were both near aphelion.

2. OBSERVATIONS

We obtained spectra of 2005 FY9 and 2003 EL61 on 2006 March 5 UT with the 6.5 m MMT telescope on Mount Hopkins, Arizona, the Red Channel Spectrograph, and a 1200×800 CCD. A 150 g mm^{-1} grating and a $1''$ slit width provided wavelength coverage of $5000\text{--}9500$ Å in first order, a dispersion of $6.38 \text{ Å pixel}^{-1}$, and a FWHM resolution of 20.0 Å . An LP495 blocking filter eliminated contamination from the second order.

¹ Observer at the MMT Observatory. Observations reported here were obtained at the MMT Observatory, a joint facility of the University of Arizona and the Smithsonian Institution.

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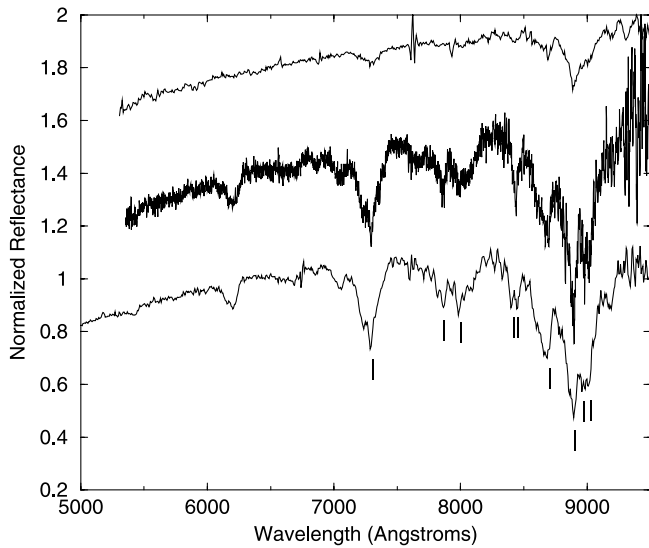


FIG. 1.— Our normalized reflectance spectrum of 2005 FY9 (*bottom spectrum*). Tick marks indicate the positions of previously reported CH_4 ice bands; see Table 1. The middle spectrum is also of 2005 FY9 (Licandro et al. 2006). The top spectrum is of Pluto (Grundy & Fink 1996). All spectra are normalized to 1 at 6500 Å. The Licandro et al. (2006) and Pluto spectra are offset by 0.4 and 0.8, respectively. Clearly, 2005 FY9 has deeper CH_4 ice bands than Pluto. Previously unreported CH_4 ice bands appear near 5400, 5800, and 6000 Å in our spectrum of 2005 FY9.

There were high, thin cirrus clouds through most of the night, and the seeing was $\sim 0.8''$. The KBOs were placed at the center of the slit and tracked at KBO rates.

We used the Image Reduction and Analysis Facility (IRAF) and standard procedures (Massey et al. 1992) to calibrate and extract one-dimensional spectra from the two-dimensional spectral images. Specifically, the electronic bias of each image was removed by subtracting its overscan, as well as a bias picture. Pixel-to-pixel sensitivity variations were removed from each image by dividing by a normalized twilight flat-field image. Extraction of one-dimensional spectra from the images was done with the *apall* task in IRAF. HeNeAr spectra were used to correct for flexure and obtain an accurate wavelength calibration. Our wavelengths are accurate to approximately one-tenth of a pixel, or ~ 0.7 Å. We removed telluric bands and Fraunhofer lines from the KBO spectra by observing the solar analog HD 112257 (Hardorp 1982) at air masses very close to 2005 FY9 and 2003 EL61 and then dividing the KBO spectra by the normalized solar analog spectra. Typically, the air-mass difference between the KBOs and the solar analog was ≤ 0.05 . The 2005 FY9 and 2003 EL61 spectra in the analysis below are an average of four and five 10 minute exposures, respectively.

3. RESULTS

3.1. 2005 FY9

We plot our reflectance spectrum of 2005 FY9 in Figure 1 (*bottom spectrum*). The tick marks correspond to previously reported absorption maxima of CH_4 ice (Table 1). The middle and top spectra in Figure 1 are of 2005 FY9 (Licandro et al. 2006) and Pluto (Grundy & Fink 1996). All spectra are normalized to 1 at 6500 Å. For the purpose of comparison, the Licandro et al. (2006) 2005 FY9 and Pluto spectra are offset by 0.4 and 0.8, respectively. Clearly, 2005 FY9 exhibits much deeper CH_4 ice bands than Pluto.

Our spectrum differs from the Licandro et al. (2006) spectrum in two ways. First, our spectrum exhibits additional subtle absorption bands at 5400, 5800, and 6000 Å. These bands have not been seen before in astronomical or laboratory spectra of CH_4 ice. Because the bands are close to the wavelengths of gas-phase

TABLE 1
LABORATORY WAVELENGTHS AND FREQUENCIES
OF CH_4 ICE ABSORPTION MAXIMA

Transition	Wavelength (Å)	Wavenumber (cm^{-1})
$3\nu_1 + 4\nu_4$	7296	13706
$3\nu_3 + 3\nu_4$	7862	12719
$3\nu_1 + 3\nu_4$	7993	12511
$4\nu_3$	8415	11884
$\nu_1 + 3\nu_3$	8442	11846
$3\nu_3 + 2\nu_4$	8691	11506
$2\nu_1 + \nu_3 + 2\nu_4$	8897	11240
$3\nu_1 + 2\nu_4$	8968	11151
$2\nu_3 + 4\nu_4$	9019	11088

NOTE.—Pure CH_4 ice *I* at 30 K (Grundy et al. 2002).

CH_4 bands and because there are strong CH_4 ice bands at longer wavelengths in the spectrum of 2005 FY9, we think the new bands are due to CH_4 ice. In addition, it appears that the band at 6200 Å is CH_4 ice as well. It is in the Licandro et al. (2006) spectrum, but they do not identify it as CH_4 ice. Second, we find a continuum slope between 5500 and 6500 Å of 10% per 1000 Å, while Licandro et al. (2006) find a slope of 13% per 1000 Å, with both spectra normalized to 1 at 6500 Å. We used HD 112257, a G2 V star, for our solar analog star, whereas Licandro et al. (2006) used BS 4486, a G0 V star, for their solar analog star. An examination of the $V - R$ colors for G0 V and G2 V stars suggests the slope difference is due to the use of different solar analog stars.

In order to place constraints on the CH_4 grain size, as well as the presence of any additional ice components on the surface of 2005 FY9, we calculated model CH_4 ice spectra. Our models use laboratory optical constants for pure CH_4 ice at 30 K (Grundy et al. 2002) and arbitrary optical constants that absorb more at blue than at red wavelengths, thereby reproducing the observed reddish slope for the 2005 FY9 continuum. The ice and reddening agent were mixed in the model at the molecular level (i.e., by means of a weighted average of the ice and reddening agent optical constants). We used Hapke theory (Hapke 1981, 1993) to transform the optical constants into reflectance spectra. We used the Hapke parameters $h = 0.1$, $B_o = 0.8$, $\bar{\theta} = 30^\circ$, and $P(g) =$ a two-component Henyey-Greenstein function with 80% in the forward-scattering lobe and 20% in the back-scattering lobe, with both lobes having an asymmetry parameter of 0.63. These values are comparable to numbers used previously to model the surface of Pluto (Grundy & Buie 2001).

Figure 2 compares the spectrum of 2005 FY9 (*black line*) and a Hapke model with a grain size of 0.55 cm (*red line*). Although the model fits the core of the 8897 Å band, it has too little absorption at all the other bands. Next, we fit the core of the weaker 7296 Å band with a 1.8 cm grain size. Then, we fit the core of the even weaker 8000 Å complex with a 2.5 cm grain size. These models illustrate a trend: weaker bands (which see deeper into the surface) always seem to need bigger grain sizes or, equivalently, greater optical path lengths in CH_4 ice.

From the above discussion, it is clear that a single grain size will not fit the observations. In Figure 3 we present a Hapke model that uses two grain sizes, 6 cm (97% by volume) and 0.1 cm (0.03% by volume), in an intimate mixture. The inability of the two-grain-size model to fit the CH_4 ice band at wavelengths less than 7000 Å in Figure 3 is due to the lack of laboratory optical constants. We note that our two-grain-size model is not a unique solution. Although this model fits the data, other models (such as coarser grains underneath a coating of finer grains) would

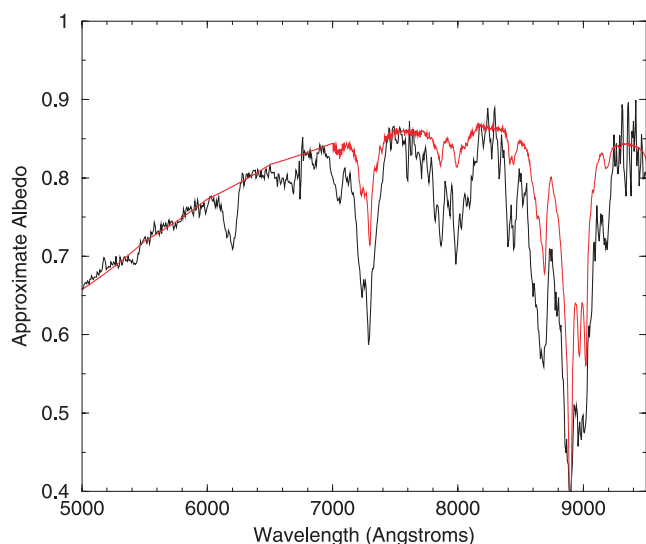


FIG. 2.— Approximate albedo spectrum of 2005 FY9 (*black line*) and a Hapke model with a reddening agent and a CH₄ ice grain size of 0.55 cm (*red line*). We assume an albedo at 6500 Å of 0.8. The model fits the core of the 8897 Å band but has too little absorption at all other bands. There are no laboratory absorption coefficients to fit CH₄ bands with $\lambda < 7000$ Å.

probably fit the data just as well. In addition, it is important to realize that grain sizes larger than 1 cm are probably a measure of the spacing of fractures or voids in the solid surface rather than indicating a surface covered by golf-ball-sized particles.

Although we can fit the shape and depth of the absorptions, there is a small but significant difference between our models and the telescope data. Specifically, the maxima of the CH₄ absorption bands in the spectrum of 2005 FY9 reside blueward of the maxima in the pure CH₄ Hapke models. In Figure 4 we present a small portion of Figure 3 centered on the 7296 Å band to illustrate the shift. Such a shift is important because laboratory experiments show that the 8897, 8968, and 9019 Å bands in spectra of pure CH₄ ice are shifted blueward by 27 Å in a CH₄/N₂ = 0.8% mixture (Quirico & Schmitt 1997).

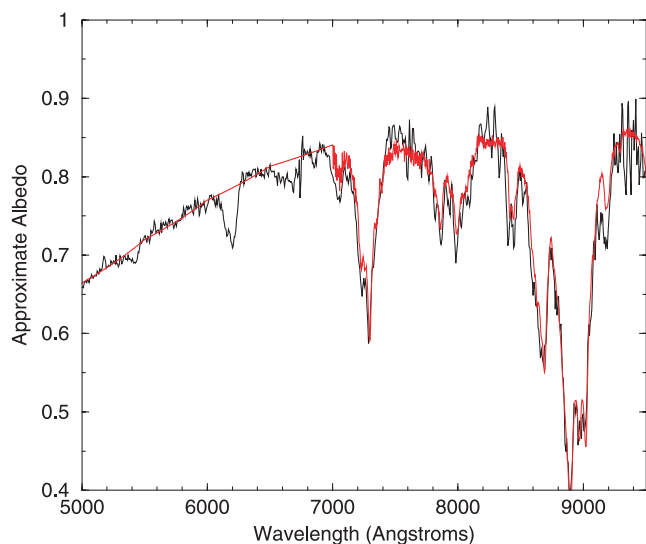


FIG. 3.— Approximate albedo spectrum of 2005 FY9 (*black line*) and a Hapke model with a reddening agent and two CH₄ ice grain sizes, 6 and 0.1 cm (*red line*). We assume an albedo at 6500 Å of 0.8. Grain sizes larger than 1 cm probably provide a measure of the spacing between fractures or voids in the surface rather than indicating a surface covered with golf-ball-sized particles. There are no laboratory absorption coefficients to fit CH₄ bands with $\lambda < 7000$ Å.

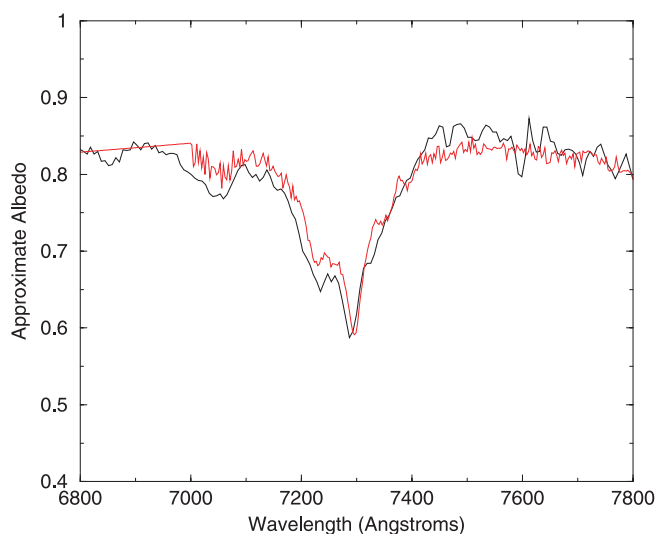


FIG. 4.— Minimum of the 7296 Å CH₄ ice band in 2005 FY9 (*black line*) blueshifted relative to the minimum of the pure CH₄ ice Hapke model (*red line*). The other bands in 2005 FY9 show a similar shift. The shift may be due to the presence of another ice component on the surface of 2005 FY9.

A cross-correlation experiment provides a way to quantify the apparent shift in Figure 3. Specifically, we wrote a FORTRAN program to shift the model spectrum from -25 to $+25$ Å in 1 Å steps. For each shift, the program finds the difference between the data and the model; i.e., it calculates $(y_{d,i} - y_{m,i})$, where $y_{d,i}$ and $y_{m,i}$ represent the ordinate values of the data and the model spectra at wavelength i . Then the program sums the squares of the differences over all N wavelength points between 7000 and 9300 Å. In other words, we calculate

$$\Delta_{\text{shift}} = \sum_i^N (y_{d,i} - y_{m,i})^2. \quad (1)$$

In Figure 5 we present a plot of the sums of the squares of the differences, i.e., Δ_{shift} , as a function of shift. We find a well-defined minimum at 3.25 Å.

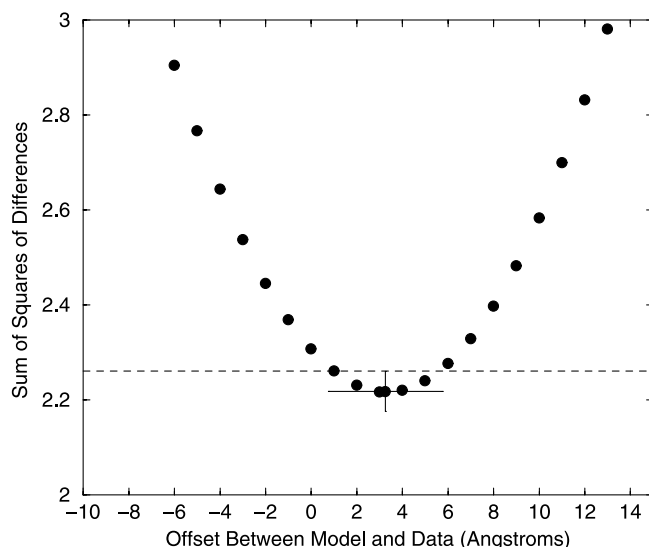


FIG. 5.— Result of cross-correlation experiment between the spectra of 2005 FY9 and the pure CH₄ ice Hapke model in Fig. 3. The differences between the two spectra reach a minimum at a 3.25 ± 2.25 Å blueshift of the data relative to the model.

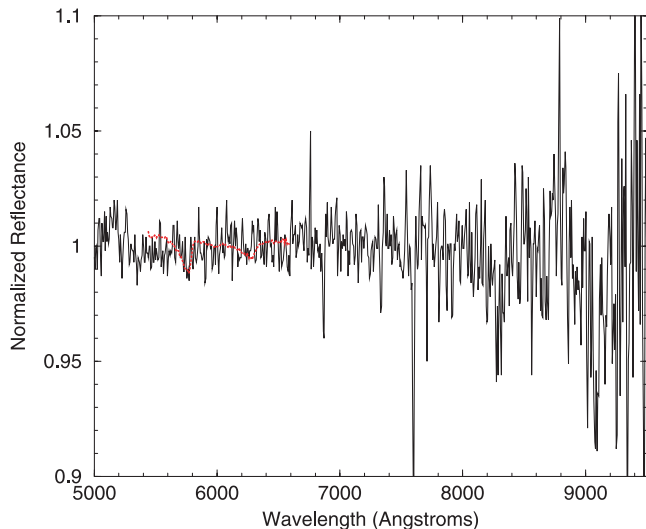


FIG. 6.—Normalized reflectance spectrum of 2003 EL61 (black line) and the spectral ratio of Ganymede to Callisto (Calvin & Spencer 1997) showing O₂ ice bands at 5773 and 6275 Å (red line). There is a tantalizing dip in the spectrum of 2003 EL61 at the position of the 5773 Å band; however, a much higher continuum signal precision is necessary to test for the presence of the weaker 6275 Å band.

What is the uncertainty in the 3.25 Å measurement? We note that HeNeAr spectra enable us to calibrate the wavelengths in the 2005 FY9 spectrum to an uncertainty of approximately one-tenth of a pixel, or ~ 0.7 Å. Specifically, we find that the average difference between the centroids of airglow lines in our data and the corresponding laboratory values is 0.7 Å. A larger source of uncertainty comes from the noise in the spectra and the broadness of the cross-correlation minimum in Figure 5. Propagation of the noise in the data and model spectra for the 3 Å shift through equation (1) gives an ordinate error bar for the minimum point (3.25, 2.218) in Figure 5 of 0.042. As a result, the uncertainty in our shift measurement is defined by $\Delta_{\text{shift}} < 2.218 + 0.042 = 2.260$ (i.e., the section of the curve below the dashed line in Fig. 5), corresponding to shifts between 1 and 5.5 Å. In short, we find that the CH₄ ice bands in the spectrum of 2005 FY9 are blueshifted relative to the model Hapke spectrum by 3.25 ± 2.25 Å.

Licandro et al. (2006) gave blueshifts of 2–6 Å for CH₄ bands in their Table 1, but they questioned the reality of the shifts because they were so small. Our independent measurement of shifts with similar magnitude bolsters the case for the reality of the small shifts. In fact, when we take the Licandro et al. (2006) data and do a cross-correlation experiment between our spectrum and their spectrum, we find no measurable shift between the spectra; but when we perform a cross-correlation experiment between their spectrum and the Hapke model, we find that their CH₄ ice bands are blueshifted 2 Å relative to the model. Our spectrum and the Licandro et al. (2006) spectrum are consistent.

3.2. 2003 EL61

We plot our reflectance spectrum of 2003 EL61 in Figure 6. The continuum has a slope of essentially zero, consistent with $B - V = 0.63 \pm 0.03$ and $V - R = 0.34 \pm 0.02$ (Rabinowitz et al. 2006). Evidently, tholins are not present on the surface of 2003 EL61 at the abundance seen on 2005 FY9. (Recall that both objects were observed on the same night and compared against the same solar analog spectrum.) We find no evidence of

CH₄ ice bands, but we can set an upper limit on the thickness of a global glaze of CH₄ ice by applying Beer's law,

$$\left(\frac{I}{I_0}\right)_\lambda = e^{-2a_\lambda t}, \quad (2)$$

to the continuum near the 8897 Å band. In the above equation, t is the thickness of the glaze, a_λ are the Lambert absorption coefficients for CH₄ ice (Grundy et al. 2002), the factor of 2 comes about because light passes through the glaze once on the way in and once on the way back out, and $(I/I_0)_\lambda$ is the ratio of light leaving the glaze to the light incident on the glaze. For $(I/I_0)_{\lambda=8897} = 0.97$, we find $t < 0.3$ mm.

H₂O ice bands are seen in near-infrared spectra of 2003 EL61 (Barkume et al. 2006). Therefore, it is reasonable to look for evidence of solid-state photolytic or radiolytic chemistry (Johnson 1990; Johnson & Quickenden 1997; Delitsky & Lane 1997) by seeing whether O₂ ice is present on the surface of 2003 EL61. In Figure 6 we superpose the 5773 and 6275 Å O₂ ice bands in the spectra of Ganymede (Calvin & Spencer 1997) on our 2003 EL61 spectrum. There is a tantalizing dip at 5773 Å in the spectrum of 2003 EL61 but no dip at the weaker 6275 Å band. The continuum signal precision at the position of these bands is about 150, so if the 5773 Å band is real, it would take a continuum signal precision of about 300 to detect the 6275 Å band.

We estimate an upper limit to the thickness of a global glaze of O₂ ice by assuming that the possible feature at 5773 Å is real and then applying Beer's law as we did for CH₄ ice. For $(I/I_0)_{\lambda=5773} = 0.99$ and $a_{\lambda=5773} = 5.5 \text{ cm}^{-1}$, we find $t < 0.01$ mm. Our value for $a_{\lambda=5773}$ comes from an integrated absorption coefficient of $1.1 \times 10^3 \text{ cm}^{-2}$ and a band FWHM of $\sim 200 \text{ cm}^{-1}$ (Landau et al. 1962).

4. CONCLUSIONS

Our spectrum of 2005 FY9 exhibits strong CH₄ ice bands, in agreement with the spectrum of Licandro et al. (2006). From a comparison of our spectrum and a Hapke model, we find that the 2005 FY9 CH₄ ice bands are shifted 3.25 ± 2.25 Å blueward relative to the positions of pure CH₄ ice bands. The shift could be due to the presence of another ice component, possibly N₂ ice, CO ice, or Ar. Future higher resolution spectra of the individual CH₄ bands should determine whether the weaker bands that penetrate deeper into the surface exhibit different shifts than the stronger bands that do not penetrate as deep into the surface. Such observations could provide a technique to measure the CH₄ concentration relative to the other ice component as a function of depth below the surface of 2005 FY9. In addition, it is highly desirable to obtain a measure of the shift as a function of rotational longitude on 2005 FY9 for a particular CH₄ ice band. Such a technique could provide a measure of inhomogeneity on the surface of 2005 FY9. Grundy & Fink (1996) made such measurements for the 8897 Å band on Pluto and found that the blueshift varied from 0 to 10 Å over the surface.

On Pluto, it appears that N₂ is sufficiently mobile to form textures that allow incoming photons to travel several centimeters through the very transparent, polycrystalline N₂ ice before the photons are scattered off inclusions or grain boundaries. The long path lengths make it possible for a small amount of CH₄ relative to N₂ to give deep CH₄ absorption bands. The mobility of CO is only a little less than N₂, and the mobility of Ar is only a little less than CO. Therefore, it is possible that CO ice or Ar ice could provide the host matrix for long optical path lengths. It is also possible that the host matrix is a combination of N₂, CO, and Ar. A suite of laboratory experiments that measure the shifts

of CH₄ absorption maxima for different concentrations of CH₄ relative to N₂, CO, and Ar would be highly valuable for the future interpretation of observational data.

Our spectrum of 2003 EL61 is remarkably featureless. There is a hint of a band at 5773 Å possibly due to O₂ ice. Future work will attempt to double the signal precision of the continuum to at least 300, which is the level that appears to be required for any possible detection of the weaker O₂ ice band at 6275 Å. The detection of O₂ ice in significant quantities on KBOs could be of considerable interest in the distant future as a source of spacecraft fuel.

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